ON THE PROSPECT OF OBTAINING RADIAL VELOCITIES BY MEANS OF THE OBJECTIVE PRISM.

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Among the many problems that confront the workers in stellar spectroscopy at the present time, three stand out by reason of their importance. First, the classification of stars by means of their spectra. Second, the determination of absolute radial velocities for the purpose of determining the sun's way, and the relation between stellar spectra and stellar motions; and of throwing light upon various hypotheses regarding star-streaming. Third, the determination of the orbits of spectroscopic binaries.

In the second and the third of these problems the need of extending our determinations of radial velocities to faint stars has become very pressing. At the present day a comparatively large number of observatories are equipped with apparatus that, without involving unduly long exposures, will yield radial velocities for stars down to the fifth magnitude; but what is greatly desired is an extension to stars at least as faint as the eighth magnitude. It is futile to hope to attain such an extension by erecting more powerful telescopes and by attaching to them slit spectrographs of even the most approved design. Experience has amply shown that in work of this kind the gain that comes with increasing the size of the telescope is only very slight. The principal reason for this is the loss of light at the slit, which under favorable circumstances in the case of telescopes of the largest size must frequently be as much as ninety per cent.; and under certain atmospheric and instrumental conditions this percentage of loss may be considerably increased. With smaller telescopes the loss of light at the slit is not so serious, and for this reason, as well as for others, it is a fact (to cite somewhat extreme cases) that the spectrographs attached to certain telescopes having apertures from twelve to fifteen inches have proven nearly as efficient for the determination of radial velocities as those attached to telescopes of two or three times their aperture.

If, therefore, we are to seek any considerable extension of these observations to fainter stars, we are forced to turn to the objective prism, the great advantage of this form of spectroscope being its economy of light. Few slit spectrographs now in use utilize more than one per cent. of the light that falls upon the objective of the telescope to which they are attached. With the objective prism, as much as twenty-five per cent. may easily be realized with a proper choice of materials in the objective and in the prism, and providing also that the thickness of the prism is not too great. Furthermore, with the slit spectrograph we secure the spectrum of only one star at a time, whereas with the objective prism all the stars in a considerable area of the sky impress their spectra upon the same plate. On the other hand, the difficulty of securing points of reference from which the shifts in the lines may be measured has thus far proved an insurmountable obstacle in the way of obtaining even fairly accurate velocities by this means.

Spectra produced by diffraction gratings are nearly normal; that is, the distance between any two lines is approximately proportionate to their difference in wave-length. In such spectra the shift due to velocity is greater for lines of greater wave-length. Consequently, the spectrum is lengthened if the star is receding from us and is shortened if the star is approaching. On the other hand, spectra produced by prisms are far from being normal, lines in the region of greater wave-length being crowded together, while those at the violet end are more widely separated. In this case, shifts due to velocity become reversed in their relative amounts, being now greater for lines of shorter wave-lengths. Prismatic spectra are accordingly shortened for receding stars and lengthened for those that are approaching us. We see, then, that the lengths of both prismatic and diffraction spectra are changed by radial velocity, and accordingly the latter can, theoretically at least, be found by measuring the distance between two lines widely separated in the spectrum.

The possibility of determining velocities in this way seems first to have occurred to Pickering, who suggests and dismisses it in a single sentence, on page xxi, Volume 26, *Annals of the Harvard College Observatory*. A few years later the same method was independently proposed in a somewhat different form by Orbinsky[1] and also by Frost.[2] None of these suggestions seems to have been taken up by astronomers, and so far as I know there is no record of any actual experiment dealing with the length of spectrum from the point of view of radial velocity.

Whatever may have been the promise held out by these proposals when they appeared twenty years ago, I should like to point out that their chance for leading to valuable results may be greatly increased by the use of modern photographic plates. Recently several investigators have shown us how to prepare plates that are sensitive throughout a far greater range in wave-lengths than was hitherto the case. Formerly, only the region to the violet side of the F line (λ 4,860) could be photographed without necessitating very long exposures; but now we have at our disposal comparatively rapid plates that will yield spectrograms of nearly uniform density from the K line at λ 3,933 to the D lines at λ 5,895, or even to the C line at λ 6,563. With former spectra the shift in the lines in the violet region could be ascertained by referring them at best only to lines in the neighborhood of λ 4,800, which themselves share the same shift to a considerable extent. But the yellow and red portions are so closely crowded in prismatic spectra, that lines in this region would show very little shift due to velocity, and hence would form excellent points of reference for lines in the blue and violet.

To carry out this plan, an ordinary objective, whether corrected for photographic or for visual rays, would not answer, since it is necessary to have in focus at the same time lines in both regions. Cooke in England has successfully put upon the market an objective,[3] made up of three different kinds of glass, which brings into good focus the entire range of spectrum from λ 3,800 to λ 6,000. An objective of adequate aperture of this type would serve the present

[1] *Astronomische Nachrichten*, **138**, 9, 1895.
[2] *Astrophysical Journal*, **2**, 235, 1895.
[3] Designed by Mr. Dennis Taylor.

purpose fairly well. It would be still better to design an objective with this specific application in view and to bring into focus the two regions say from λ 3,900 to λ 4,500 and from λ 5,900 to λ 6,600, without paying much attention to the intermediate region, from λ 4,500 to λ 5,900.

It would be quite possible to use a reflecting telescope for this purpose. But as compared with a refracting telescope the reflector seems to be less promising for two reasons: first, because of the change in the focal length with change of temperature; and, second, because of the harmful effect of any change in the inclination of the mirror. Thus, if one edge of a mirror whose aperture is one tenth its focal length should be tilted with respect to the other edge by only one micron, the lines in the spectrum would be shifted by twenty times this amount, a quantity that is of the same order as the shift due to velocity. In refracting telescopes the effect of a slight tilt in the objective is of no consequence whatever.

With the objective prism it is difficult to make long exposures that will show sharp spectra. This is chiefly because the refractive index of glass varies rapidly with the temperature and the amount by which the rays of light are deviated is thus continually changing if the prism is in the open air. Observers with slit spectrographs have long been aware of the necessity of guarding their prisms against changes of temperature, and have learned to surround them with cases within which the temperature is artificially kept from fluctuating. As I pointed out a few years ago,[4] there is no reason why a similar device should not be used in connection with objective prisms. In this case, the light from the star should first be admitted through a window of optically plane parallel glass, whose aperture is the same as that of the prism and the objective. This window should form part of a temperature case enclosing the whole camera, including the prism, the objective and the plate-holder. The case can then be maintained at constant temperature in the usual way.

Even with these precautions it would be well, in the experimental stages at least, to calibrate the prism frequently by means of stars whose velocities are known from observations with slit spectro-

[4] *Science*, 30, 729, 1909.

graphs. More than a thousand such stars are available at the present time and in a few years this number will be at least doubled; so that there should never be any great difficulty in finding a suitable test object close at hand. The process of observing would then perhaps consist of an exposure on a star whose velocity we wish to determine, immediately followed in each case by an exposure (made on the same plate close to the first) on a neighboring star whose velocity is already known. The difference of the lengths of these two spectra is then to be measured, converted into units of kilometers per second and applied to the known velocity.

A quarter of a century ago the suggestion was made by Pickering, in connection with his experimental work for the Draper Memorial, that radial velocities could be determined from objective prism spectra if some absorptive medium could be found that would produce one or more narrow and sharp absorption bands. If such a substance were interposed at any point in the spectrograph, or indeed anywhere between the star and the plate, the resulting spectra would also show these bands in positions not affected by the velocity of the star, and would thus offer a beautifully simple method for determining velocities. Pickering made a search for a substance with this very desirable quality, but at that time did not succeed in finding a satisfactory one. Recently, however, he suggested this subject to Professor R. W. Wood, who after experimenting with various compounds has proposed neodymium chloride for this purpose. This substance introduces into the photographic region of the spectrum a number of absorption bands. One of these, at λ 4,272, is sharp and fairly narrow, having a width of about three angstroms, a quantity that corresponds to a velocity of about 200 kilometers a second. This substance seems, therefore, to offer a method for measuring the velocities of certain stars with a moderate degree of precision. Just how accurately this can be done, we must wait for actual experiments to tell us; and such experiments are under way in at least two observatories. There can be little doubt that an accuracy represented by a probable error of not more than ten kilometers can be attained in this way. This Pickering-Wood method is hardly applicable to any but stars of the A and B types. In stars of the F type and beyond, the neodymium line or band at λ 4,272 becomes involved with lines that are proper to the star itself, and accurate settings upon it become impossible.

A number of other suggestions have been made for utilizing the objective prism for determining velocities, but I shall stop to consider only one of these. Like the two proposals that we have already described, this method owes its origin to Pickering,[5] who seems to have studied this problem to good purpose long in advance of any other astronomer. Let us suppose that we have secured by means of the objective prism a photograph showing the spectra of a number of stars in the same region, and that the prism has been so oriented that the violet end of each spectrum is toward the north. Suppose further that we have measured accurately the position of the K line in each spectrum. From these measurements we might compute the relative declinations of the stars, but these declinations would be in error by a slight amount on account of the unknown radial velocities of the stars. Thus a star that is approaching us would have its K line shifted toward the violet end, or in this case, toward the north, and the computed declination would be too great. Let us then secure another photograph of the same region with the prism reversed, so that now the violet end of each spectrum is toward the south. The approach of a star would as before shift its lines toward the violet, which is, however, now toward the south. We should therefore derive a relative declination for the star that is as much too small as it was too great in the first instance. It is obvious, then, that the measurement of such a pair of plates would theoretically give us the data from which the relative velocities of all the stars on the plate might be inferred. Pickering further proposed that the prism be reversed by simply reversing the telescope on its equatorial mounting, and that the comparison of the two plates could be facilitated by taking one of them with the glass side outward. The plates could then be put film to film and the measurements would become differential.

Although the theory of this method is simple enough, its practical

[5] Harvard College Observatory Circulars, No. 13; see also *Astronomische Nachrichten*, 171, 137, 1906.

application is a matter involving serious difficulties. A number of modifications have been proposed with a view to obviating one or another of these difficulties. Thus Stewart[6] suggested that, instead of making exposures upon two different plates, two objectives and two oppositely placed prisms be employed for making two simultaneous exposures side by side upon the same plate. The plate would then have to be inclined equally to the two incident beams, and, under ordinary circumstances, it would be possible to secure only one pair of spectra upon each plate. Another modification is that due to Comstock,[7] who proposed that the two halves of the objective be covered by two prisms having their refracting edges turned toward each other. These prisms are to be compound and of the "direct-vision" variety, so as to yield for each star a pair of spectra in close juxtaposition. Here, however, we encounter the difficulty of securing prisms of sufficient size, for prisms of this description would have to be very thick in order to give spectra of sufficient dispersion. The present writer has suggested still another modification,[8] in which the two plates are taken simultaneously by means of two independent (but similar) cameras and prisms, both being enclosed in a constant temperature case provided with two suitable windows of plane parallel glass.

The advantages of securing the two photographs at the same time are two-fold; first, this obviates any necessity for considering refraction, a very bothersome matter when large fields are in question. Second, the so-called guiding error is eliminated. Whether the telescope is driven entirely by clockwork, or whether the observer attempts to secure more perfect guiding by introducing slight corrections by hand, the spectra will still wander a little from their mean positions and the place at which an observer will bisect a line in the spectrum will depend somewhat upon the nature of the guiding. If, however, the direct and the reversed spectra are secured simultaneously, the guiding error will be the same for both and will have no effect upon the derived velocity.

In this method of determining velocities there remains a difficulty

[6] *Astrophysical Journal,* 23, 396, 1906.
[7] *Astrophysical Journal,* 23, 148, 1906.
[8] *Science,* 30, 729, 1909.

more serious than any that we have mentioned. This is the distortion of the field due to the presence of the prism. Let us suppose that there were in the sky a row of stars in the same right ascension and equally spaced in declination. Let us photograph the spectra of these stars with the help of an objective prism whose refracting edge is parallel to the equator. Then, quite apart from the effect of radial velocity, the spectra would by no means be equally spaced upon the plate, the intervals on one side of the center being all too small, and those on the other side all too great. When the prism is reversed, those spaces that were too large are now too small and *vice versa;* so that the distance between the two spectra of the same star depends upon its declination. I have computed this double distortion for a spectrograph whose dimensions are such as one would choose for this work, and have found it to amount to two millimeters at a point only two degrees of arc from the center. This quantity is about one thousand times as great as the accuracy that an observer would hope to attain in his measurements, so that it is readily seen how intimately he would have to become acquainted with his prism in order that he might apply this very large correction within the limit of accuracy that the case demands. Furthermore, there is an additional distortion of nearly the same size in the other direction. That is, if we could photograph a row of stars on the equator, their spectra on the plate would not appear in a straight line, but would lie in a curve that is approximately a parabola with its convex side toward the refracting edge of the prism.[9] If, therefore, the prism is reversed the curvature of this line is also reversed, and when the two plates are compared we again have a double distortion, depending now (in the position of the prism that we have imagined) upon the star's right ascension. It is worthy of remark that these distortions are smaller in the design proposed by Comstock than in any of the others. Furthermore, if we confine our attention to a single pair of spectra in the axis, as in Stewart's suggestion, these distortions do not enter at all.

We see, then, that the obstacles in the way of the practical appli-

[9] It is this same distortion that causes the curvature of the lines upon a slit spectrogram, the formula for which is given by Ditscheiner in the *Sitzungsberichte der Math. Klasse der k. Akademie zu Wein,* 51, part 2, 1865.

cation of this method are undoubtedly serious; nevertheless, they do not appear to be of the character that patience and perseverance on the part of a skillful observer will not overcome.

If the objective prism is ultimately to be used for determining velocities, it would be a great advantage to be able to utilize the full apertures of modern telescopes without necessitating objective prisms of corresponding size. In the case of reflecting telescopes, this might be done by replacing the flat secondary (of the Newtonian form) or the hyperboloid (of the Cassegrainian form) by a convex paraboloid, with its axis and focus coincident with the axis and focus of the primary mirror. The beam of light reflected from such a secondary would be a parallel one, contracted to perhaps one fourth or one fifth the diameter of the original beam. This reduced beam could then be made to pass through an objective prism of moderate size. Similarly, in the case of refracting telescopes, a diverging lens might be placed in the position that the correcting lens usually occupies when the telescope is to be used with a slit spectrograph.[10] This diverging lens can be so designed as to make the emerging beam of light parallel in any portion of the spectrum desired. For practical reasons it would not be advisable to contract the original beam too much; or in other words, to put the converging lens too near the focus of the visual or the photographic objective. In the case of reflectors, too, though for not quite the same reason, the paraboloid should not have too small an aperture and should not be placed too near the primary focus.

In conclusion, it seems to me that the prospect of obtaining radial velocities by means of the objective prism is good enough to warrant a trial of all three of the methods that have been reviewed above. If I were asked which of the methods seemed to me the most promising, I should say that the one which makes use of neodymium chloride would probably lead to immediate results, if we are to remain satisfied with a moderate degree of precision; but that the method which is concerned with the length of the spectrum might ultimately be developed to give considerably more accurate results.

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[10] Compare with the paper by Wadsworth, *Astrophysical Journal*, 16, 12, 1902.